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The All Electric Warship
From Vision to Total Ship System Integration

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ABSTRACT

Energy weapons and advanced sensors developed to enable future Navy combatant missions could have ship service power requirements equal to or greater than propulsion. These new electric power requirements make the All Electric Warship different from combatants of the past, and Integrated Power Systems (IPS) will likely be required to enable these weapon and defense systems to be deployed affordably. Designing and developing cost effective power systems that meet future ship mission requirements is accomplished through a Total Ship Systems Engineering (TSSE) process. Navy mission needs are rarely well defined or static so it is critical that the TSSE methodology be flexible and capable of evaluating alternative emerging technologies consistently and efficiently. This same process is also utilized to define and guide the research and development necessary to ensure that the power systems will be available for Navy use. This paper will provide a brief background of Navy Integrated Power System development programs, and address the plans for ensuring that cost effective power systems are available to make the All Electric Warship a reality.

INTRODUCTION

The United States Navy has taken a major step toward the all-electric warship by committing to the utilization of Integrated Electric Power Systems on the next surface combatant. It is anticipated that utilization of electricity as the sole means of energy transmission and electrification of all feasible loads will improve both mission effectiveness and cost effectiveness of future ships. Navy warship propulsion power requirements have traditionally far exceeded those of ship service loads. However, future ship missions that require high energy weapons and sensors will likely make ship service power loads equal to or greater than propulsion loads. Dependence on these new systems to meet new mission requirements could also make their power availability a higher priority than ship propulsion power. It is these new electric power requirements and priorities that make the All Electric Warship different from combatants of the past, and Integrated Power Systems are envisioned to enable these weapon and defense systems to be deployed affordably. Designing and developing cost effective power systems that meet future ship mission requirements is accomplished through a Total Ship Systems Engineering (TSSE) process. Future Navy mission needs are rarely well defined or static so it is critical that the TSSE methodology be flexible and capable of evaluating alternative emerging technologies consistently and efficiently. This same process is also utilized to define and guide the research and development necessary to ensure that the power systems will be available for Navy use. This paper will address the current status of IPS development, and what remains to be accomplished to make the All-Electric Warship a reality.

A BRIEF HISTORY OF INTEGRATED POWER SYSTEMS

Although the US Navy has used electric propulsion power transmission for various reasons in the past, the modern era of electric drive began with research into superconducting electric propulsion motors in the late 1960's. Higher power density, quieter operation, and better

control than conventional motors were anticipated to result in improvements in ship mission capabilities. The Integrated Electric Drive (IED) Program established in the 1980's expected that further improvements in warfighting capabilities could be achieved by integrating the ship service power system with the propulsion power system. When the cold war ended in the 1990's the program refocused toward affordability and it was renamed the Advanced Surface Machinery Program (ASMP). The new goal was to identify, develop, and deploy on all Navy ships the most cost effective power systems that met mission requirements. Mission requirements for future ships considered in this program were defined as those currently in effect at the time, and most cost effective was defined as the set of power systems that produced the lowest total cost of ownership for the Navy. A total ship systems engineering (TSSE) process was developed to define the set of ship power systems that would be prescribed for future ship acquisitions. Total ship systems engineering was necessary because specific attributes of alternative technologies or systems do not necessarily accurately reflect their complete impact on cost effectiveness. For example, the electric transmission of power is less efficient than mechanical transmission. However, the flexibility of electric transmission could allow a ship using it to have a higher overall system efficiency (as reflected by fuel consumption) compared to the same ship using mechanical transmission. Another example could be specific power of electric motors. A motor with higher specific power does not necessarily produce a more cost-effective ship. If the motor has to sacrifice efficiency or costs more to construct than a lower specific power motor, then the affect could be to decrease the cost effectiveness. A total ship systems engineering process is the only way to properly consider all the relevant impacts a technology, component, or system has on cost effectiveness. The Advanced Surface Machinery Program began power systems engineering evaluations and design and procurement of an advanced development Integrated Power System for testing at a land based engineering test facility. The R&D system was intended to provide more accurate characterizations of conceptual integrated power systems to be evaluated in the systems engineering process. Department of Defense Acquisition Reform assigned the responsibilities for producing ship designs (and their power systems) to private industry teams rather than being developed and prescribed by the Navy. This prompted a decision in the mid-1990's to incorporate the Navy power system development program into the Surface Strike Program Executive Office (PEO (S)), as the Integrated Power Systems (IPS) Program Office (PMS 510). The Advanced Surface Machinery Program was terminated before finishing the fleet TSSE evaluations so no complete results are available. However, there are examples of partial utilization of the process. The Navy completed a Cost and Operational Effectiveness evaluation of Navy generated conceptual designs for a surface strike combatant (SC 21). Characterizations of the ship options were generated according to the TSSE method described below, and Table 1 provides a comparison of the ASSET conceptual ship design weight summaries for a ship with an integrated power system compared to a ship with a mechanical propulsion and segregated power system.

Mechanical Drive Segregated Power System	
Lightship Weight = 5651 LT Fuel Load = 991 LT	
Integrated Power Systems	% Change
Lightship Weight = 5436 LT	-4%
Fuel Load = 821 LT	-17%

Table 1. SC 21 Conceptual Ship Design Comparison Summary

These results showed a reduction in ship weight without fuel (lightship weight), and a substantial reduction in fuel load, both contributing to a lower ship cost.

The Surface Strike Program Office awarded contracts to two industry teams to prepare proposals for the design, construction, and life cycle maintenance of the next Navy combatant. Navy generated IPS characterizations and

evaluations (NAVSEA, PMS 510, 1997) were provided to the industry teams and both teams selected integrated power systems for their proposed ship designs. In January 2000, the Secretary of the Navy declared the Navy's commitment to integrated power while announcing the research and development budget for this ship acquisition.

TOTAL SHIP SYSTEM ENGINEERING PROCESS

The TSSE process created for the Advanced Surface Machinery Program is a specific application of system engineering in general. The following excerpt is a definition of Total Ship Systems Engineering from DOD 5000.1 Series Instructions:

A Set of Processes to Translate Operational Needs and/or Requirements into a System Solution – Including a Top Down Iterative Process of Requirements Analysis, Functional Analysis and Allocation, Design Synthesis and Verification, and Systems Analysis and Control – Through Concurrent Consideration of All Life-Cycle Needs.

Total ship system engineering evaluations all follow the same fundamental process:

1. Definition of Mission/Ship Requirements or Performance Characterizations (mission requirement driven – "requirements pull", or technology enabled – "technology push")
2. Characterization of Feasible Equivalent Conceptual Ship Designs
3. Definition of Evaluation Trade-off Factors
4. Quantification/Ranking of Trade-off Factors (including quantifying the relative importance of each)
5. Quantification of System Figures of Merit from the Trade-off Factors

A Total Ship Systems Engineering evaluation produces a set of "most effective" (according to the evaluation criteria chosen) equivalent conceptual ship designs to meet a corresponding set of mission/ship requirements.

Cost Effectiveness Evaluations

The Navy power system TSSE process utilizes Total Cost of Ownership (Cost Effectiveness Evaluation) and Risk as trade-off factors. A Cost Effectiveness Evaluation produces a set of systems (designed to meet a corresponding set of equivalent mission/ship/performance requirements), that have the lowest Total Ownership Costs (TOC). The final ship design is selected through an Assessment of Alternatives (AOA) (also known as a Cost and Operational Effectiveness Analysis (COEA)). A COEA is not part of total ship systems engineering, but a decision making process based on a trade-off of mission needs and costs.

Definition of Mission/Ship Requirements or Performance Characterizations

Mission/ship requirements are produced for all future ship applications on which alternative systems will be evaluated. Requirements/performance characteristics can be established in two ways:

1. Mission requirements that define how the ship and ship power system must perform in order to meet them (known as "requirements pull").
2. Mission capabilities enabled through the characteristics/capabilities of the ship systems (known as "technology push".

Mission requirements for future Electric Warships can also be formulated by either method. For example, a specific shore fire support mission may require delivery of a defined amount of energy at some defined distance. This would translate to a weapons requirement for the ship, and that, in turn, would translate to an electric power requirement. The mission may also place a requirement on the propulsion load. These become part of the requirements the power system must be designed to meet. The alternative could be to define a power system according to specific attainable performance characteristics and translate those into specific mission capabilities. Current conventional weapons systems do not

require large amounts of electrical energy (compared to the propulsion power), and, therefore, changes in ordnance delivery will not have a large impact on the power system trade-off. However, the Electric Warship and its' electric ordnance delivery system will experience sizable changes in electric load requirements with changes in delivery requirements.

Characterization of Feasible Equivalent Conceptual Ship Designs

Feasible equivalent conceptual ship designs are produced for each set of Ship/Mission requirements. There will probably be many alternative systems/designs/ship types/etc. that can be technically configured to meet requirements. The conceptual ships configured around these alternative power systems must be designed to the same groundrules/guidelines/margins/etc. (i.e. "equivalent"ship designs) for the comparisons/tradeoffs to be meaningful. The Navy utilizes an analytical conceptual ship design computer program called the Advanced Surface Ship Evaluation Tool (ASSET) to perform many of the characterizations necessary in producing equivalent conceptual ship designs. However, there are many required iterative processes that currently must be accomplished externally and integrated into the design, (i.e. Vulnerability, Survivability, Detectibility, Costing, Seakeeping, etc.). It is a Navy goal to combine all these processes into a single conceptual ship analytical design tool – a Smart Product Model. This design tool will be "Smart" because it will iterate the designs of all conceptual options to the same given set of conditions and ship/mission requirements.

Definition of Tradeoff Evaluation Factors

Trade-off factors are defined as those ship characteristics that will be used to quantify the effectiveness of the ship in meeting the mission requirements. It is the intent of the Electric Warship Program that fleet life cycle cost and risk in achieving the defined system characterizations are the factors utilized in the tradeoffs, although other factors, or combination of factors, could be used.

Quantification/Ranking of Trade-off Factors

LIFE CYCLE COST

Life cycle cost is comprised of all the expenditures (that are directly or indirectly related to the defined systems) incurred by the Navy over the life (or a defined time frame) of the applications. These expenditures have been categorized into forty-four defined cost elements in order to facilitate life cycle cost calculation. These elements are divided into three categories to allow cost evaluations to be done at the fleet level as well as at the class or ship level:

1. Fleet Costs -- Costs incurred to introduce or support equipment or systems in the Navy, independent of the number of applications. (i.e. Research and Development, TECHEVAL/OPEVAL, Land Base Test Site Development, Recurring Life Cycle Management, etc.)
2. Class Costs -- Costs incurred with each new ship class application, independent of the number of ships in the class. (i.e. Ship Design Costs, etc.)
3. Ship Costs -- Costs incurred with each ship application. (i.e.. Ship Construction Costs, Fuel Costs, Repair Costs, etc.)

Life Cycle Costs are also categorized as:

1. Acquisition and Fleet Introduction (A&FI) Costs incurred to a fleet, class, or ship to support introduction of equipment or systems.
2. Operation and Support (O&S) Costs incurred on a recurring basis to support operation of equipment or systems.

RISK

There are many ways to quantify risk. A definition developed for the ASM Program is a relative measure of the uncertainty associated with

producing defined technologies and systems (with defined performance characteristics and ship/system impacts) within the times and costs estimated.

Quantification of System Figures of Merit

A System Figure of Merit is a single quantified value that represents the "goodness" of that system to the ship. It is determined by combining the values of the trade-off factors, and is compared to the corresponding values of competing alternative systems.

FUTURE FLEET FORMULATION AND ELECTRIC WARSHIP

The Navy is embarking on a process to smoothly transform the Operational and next Navy into the Navy after next by focusing on mission capabilities at the Joint Battle Force level rather than at the individual ship level. This process facilitates evolutionary acquisition, implementation of time-phased requirements, and agility in response to emerging threats. The fleet identified by this proposed Future Force Formulation (F^3) Program is expected to include ships utilizing weapons, propulsion systems, launchers, sensors and countermeasures that will permit detection and engagement of the enemy far outside the envelope for counterattack. Realization of these future ship systems is dependent on the availability of cost effective power systems to enable or support their missions. The Electric Warship program, operating from a consistent and coordinated Total Ship Systems Engineering (TSSE) process, will identify and develop these necessary and cost effective future ship power systems.

Chief of Naval Operations Strategic Studies Group

The Chief of Naval Operations Strategic Studies Group (SSG) has developed a specific mission operational concept (*Sea Strike)* incorporating as part of the combat mission "overwhelming precision firepower"(SSG XVIII 1999). They further stated that "the electromagnetic (EM) gun is the critical component of the engagement portion of *Sea Strike* "because of its affordability and range" and that "development of integrated shipboard propulsion, necessary to support a naval EM gun system, should also be included".

As part of a follow-up investigation the SSG had several conceptual combatant ship designs configured with and without an EM gun (also known as a Rail Gun). Tables 2&3 provide lightship and full load weight comparisons for two of these alternatives with and without the same 60 MW Rail Gun (Koleser 1998).

Conceptual Ship Design	Lightship Wt. (Tonnes)	% Change
Mechanical Transmission/Segregated Power/without Rail Gun	10282	+15%
Mechanical Transmission/Segregated Power/with Rail Gun	11849	
Electric Transmission/Integrated Power/without Rail Gun	10278	+4%
Electric Transmission/Integrated Power/with Rail Gun	10681	

Table 2. Lightship Weight Comparison

Conceptual Ship Design	Full Load Wt. (Tonnes)	% Change
Mechanical Transmission/Segregated Power/without Rail Gun	13249	+17%
Mechanical Transmission/Segregated Power/with Rail Gun	15434	
Electric Transmission/Integrated Power/without Rail Gun	13345	+6%
Electric Transmission/Integrated Power/with Rail Gun	13142	

Table 3. Full Load Weight Comparison

These results show that installation of a 60 MW Rail Gun on a ship with mechanical transmission

and a segregated power system incurs a much larger weight penalty than installation on a ship with electric transmission and an integrated power system. The results also show that the full load weight of the IPS ship with the rail gun is 15% lower than that of the mechanical drive ship with the rail gun. The stated conclusions are; 1. "Installation of Pulse Energy Weapon Systems (Rail Gun) on mechanical drive ships has a significant impact on ship full load displacement. It will also impose a significant cost impact", and 2. "Installation of Pulse Energy Weapon Systems (Rail Gun) on IPS ships does not have a significant impact. Also, expected cost impact is significantly less." The requirement for gun power was based on a defined land attack mission that did not specify the ship operational capabilities. An assumption was made for the ship impact study that the ship would only fire at speeds less than 15 knots. This assumption has no impact on the ship with segregated power because the gun and propulsion each have their own dedicated power sources that must each meet their respective maximum requirement. However, the ship with integrated power has a single set of power generators to provide power to propulsion, ship service, and the gun. The power generation capacity installed on the IPS ship depends on the operational requirements of all the loads, and how those requirements affect the apportioning of power. The requirement that the ship fire at speeds below 15 knots produced a total installed generation capacity equal to the gun load plus the ship service load plus the propulsion load at 15 knots. (Note: The maximum ship speed requirement without the gun did not require power greater than the power with the gun at 15 knots). The ship with the segregated power system did not get any benefit from the ability to fire the gun at any ship speed. A higher speed requirement for gun use would produce an IPS ship having a larger power generation capacity resulting in a larger, more expensive ship. Fortunately, the fact that propulsion power is approximately proportional to the cube of ship speed means that only $1/8^{th}$ of installed power would be required to make ½ speed. A ship with integrated power systems configured with the same installed propulsion power as a ship with mechanical transmission and segregated power systems would have $7/8^{th}$ of installed power available for the EM gun while cruising at ½ speed. The segregated power ship would remain the same despite any change in speed requirement for gun use. Perhaps Integrated Power Systems could provide a more cost-effective solution even if the IPS and segregated system conceptual ship designs were produced to the same speed/firing requirement, but that option wasn't evaluated.

Ship operational requirements could have a much greater impact on the design of ships with integrated power systems than on ships with segregated power systems. The sprint range of the ship is another requirement that could impact IPS ship design. Unlike a combatant that fires missiles and/or powder-propelled gun rounds, the combatant that fires a high powered electric weapon must be more concerned with its fuel reserves while sprinting to the theater of operations or risk arriving without enough fuel to fire the weapon it was sent to fire. The final ship design is determined by an Analysis of Alternatives (AOA) or Cost and Operational Effectiveness (COEA) evaluation where the benefits from increased mission capabilities are traded off against increases in costs to achieve them.

NAVY ELECTRIC WARSHIP INITIATIVES

The Navy established three coordinated initiatives within the past year to define the developments and investments necessary to meet future mission requirements through electric warships: 1. An Electric Warship Strategy Task Force was chartered by the Chief of Naval Operations (CNO) Executive Board, 2. The Naval Research and Advisory Committee (NRAC) was charged with preparing a "Roadmap to an Electric Naval Force" by the Assistant Secretary of the Navy, and 3. An Electric Warship Future Naval Capability process for focusing science and technology resources was established by the Chief of Naval Research.

The Naval Research Advisory Committee recommended a three phase plan to the Electric Naval Force:

1. The first phase (Electric Ships) will improve ship mission and/or cost

effectiveness by utilizing electricity as the sole means of ship power transmission, and making all appropriate auxiliaries electric. Emerging power system technologies will also be introduced when cost effective and fully developed for Navy use.

2. Ships in the next phase (Electric Warships) will utilize advanced weapon systems and sensors to meet future ship mission requirements. New and innovative integrated electric power systems will enable cost-effective deployment of these systems.
3. The final phase (Electric Naval Force) will export electric warship power to support offboard assets and forces ashore. This capability is supported by electrification of offboard systems and innovative power export mechanisms.

The Naval Research Advisory Committee also identified investments that will be required to execute these phases:

1. Significant and sustained weapons systems R&D investment to meet future ship mission requirements (i.e. active denial directed energy weapons, increased range and resolution radar, and electromagnetic launchers).
2. Significant and sustained Integrated Power Systems R&D investment to cost effectively meet ship mission and performance requirements (including electric power generation and transmission/distribution, electric propulsion, electric auxiliaries and resource management systems).
3. Leveraging of investments by non-Navy agencies to reduce total costs of ownership.

The Naval Research Advisory Committee highlighted the role of total ship systems engineering in the execution of the recommended technology development programs.

ROLES OF NAVY TECHNOLOGY & R&D ORGANIZATIONS

It is the Navy's goal that Electric Warships have the most cost effective power systems to meet ship missions and performance requirements. The characterization, evaluation, selection, and development of power systems to support Electric Warship will be accomplished an integrated community of The Office of Naval Research (ONR), The Naval Sea Systems Command (NAVSEA) and The Naval Surface Warfare Center Carderock Division (NSWCCD). Each organization plays a specific role in the identification, development, assessment, de-risking and transition of AEW component and systems technology.

ONR plays a central role in the identification and characterization of technologies, which enable new mission capabilities. ONR also invests in technologies, which could have near term applications to specific fleet, and Marine Corp needs. The ONR Future Naval Capabilities program is focuses on rapidly developing and transitioning technologies for specific platform or vehicle applications. The corporate laboratory for ONR is the Naval Research Laboratory (NRL) which accomplishes basic scientific research.

NSWCCD is the only Navy laboratory which accomplishes Hull Mechanical and Electrical (HM&E) R&D. NSWCCD acts as the technologists bridging the gap between Science and Technology (S&T), R&D and acquisition. This role requires the scientists and engineers understand the basic physics of a problem and to identify, develop, assess and de-risk component and systems capabilities for the Navy. NSWCCD plays a role in support of both ONR and NAVSEA programs. NAVSEA establishes ship performance characteristics from operational requirements set by OPNAV. Developing these requirements supports the identification of candidate technologies to meet Navy needs. These requirements support ONR in identification and investment in concepts to meet future Navy needs. NAVSEA also accomplishes a role of technical authority for the Navy in HM&E.

CONCLUSION

Future Navy warship missions are envisioned to require weapon and sensor systems with electric power requirements as large and important as propulsion. Power systems to support these electric warships will require a design and development program utilizing consistent and flexible total ship systems engineering processes and coordinated among all Navy organizations. The same TSSE processes should be utilized at every phase of technology maturity, from the identification and prioritization of research and development, to the selection of the most cost-effective systems for ship acquisition.

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